

Economical 10-meter-class ground-based receiver for deep-space optical communications

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ABSTRACT

Modifications to an existing radiofrequency telescope are described which would enable it to operate as an R&D optical receiver terminal for deep-space communications. The low overall cost of the telescope is due to the unique process of fabricating the 10.4 meter primary mirror and its support structure, the lightweight of the primary ($10\text{--}11\text{ kg/m}^2$), and the requirement that the telescope act only as a photon bucket, which lowers the cost of optically figuring and polishing the mirror. The entire optical ground terminal facility is estimated to cost approximately \$10 M to construct.

1. INTRODUCTION

The optical communications program at JPL has been investigating designs for ten meter class telescopes for deep-space communications.^{1,2,3} The long range goal is to develop an optical subnet as an adjunct to the existing Deep Space Network (DSN) which operates at radiofrequencies. As currently envisioned, this subnet may incorporate as many as six to twelve ten meter telescopes deployed worldwide.⁴ The cost of such a subnet will be prohibitively expensive if a high quality imaging optical telescope such as Keck were used as the basis for a single, communication terminal (the cost for the entire Keck facility is about \$93 M, the cost of the primary mirror alone is about \$17.3 M).

Steps to containing the cost of a single terminal facility include 1) minimizing the fabrication cost of the primary mirror, 2) minimizing the telescope length thereby reducing the size of the enclosure required to house it, 3) minimizing the weight of the telescope and its support structure, which relaxes the mechanical and structural performance required of the tracking gimbal, and 4) utilizing the infrastructure of suitable existing sites to keep new building and other construction costs (such as roads) as low as possible.

once the primary clear aperture size and substrate are selected, the methods of coarse fabrication are usually limited to just several choices. The optical prescription, figure quality, and roughness requirements determine the amount of figuring and polishing needed - the most labor intensive phases. For Cassegrain telescope configurations, the telescope length is determined by the f-number of the primary - a fast primary provides short overall length. The overall weight of the telescope is also driven mostly by the weight of the primary. A heavier primary requires support structures of materials of high stiffness and generally greater mass, so that system natural frequencies are higher than those of anticipated disturbance forces. Clearly, the primary mirror is the single most important component driving the cost of a large terminal.

Link analyses for the outer planets led to requirements for a primary aperture size of ten meters, Cassegrain configurations were selected for simplicity, and an F/# of 0.5 was selected to keep the telescope length as short as possible. These deep-space links can utilize pulse position modulation schemes very effectively,⁵ which implies the ground receiver terminal is not required to faithfully preserve the phase of the incoming optical signal, only detect the presence or absence of an optical pulse during a time interval. Hence the telescope functions as a photon bucket and the figure quality of the optics can be much less stringent than that required of an imaging telescope. These concepts are being used to define the requirements for a proposed Deep Space Optical Receiving Antenna (DSORA). Mirror substrate considerations included glasses, metals, and certain sandwich compositions, such as aluminum between graphite epoxy (G/E) sheets. Silicon carbide was assessed as requiring fabrication process development well beyond current capabilities to produce such a large optic inexpensively and was eliminated from consideration. Normal ULE glass costs about \$6.5 M for a ten meter primary but weighs 110 kg/m.² The lightweighted form would weigh 11 kg/m² but cost \$17-22 M. Both glass options are unattractive. The majority of new large aperture telescopes being designed use

segmented primaries and since the major goal is to keep cost low, constructing the photon bucket following an existing segmented design was judged to be the most feasible and cost effective path to follow.

While the telescope's optical quality is quite coarse and the figure of merit is overall blur size, there is an additional need to control surface scattering. Due to the operational requirement to provide twenty-four hour linkage, solar scattered irradiance from the telescope optics and from any support structure in the field of view (FOV) of the detector can be a major contribution to the total optical background noise. Parasitic scattering from telescope optics is reduced to acceptable levels through substrate selection and polishing - a BRDF (Bidirectional Reflectance Distribution Function) requirement is specified. Scattering from structural surfaces is minimized by keeping surfaces out of the field of view altogether, or by carefully locating hardware with smooth surfaces and highly absorbing matings. The major source of background noise remaining - atmospherically scattered solar radiation in the FOV of the detector - is reduced to an acceptable level by using the extremely narrow passband (0.01 \AA) provided by a Stark-tuned, Faraday Anomalous Dispersion Optical Filter.⁶

In spite of efforts to contain cost, estimates for fabrication and construction of the ten meter optical terminal were still large. A more generalized approach was adopted to find the least expensive means of constructing a photon bucket with the design characteristics of DSORA, and this included using or adapting existing telescopes. The millimeter wave Leighton telescope was known to be of the required aperture size and the construction cost was very low. The primary substrate was aluminum, and the telescope operated during both daytime and nighttime. This paper reports the technical modifications to the Leighton telescope which would enable operation as the DSORA photon bucket. Cost estimates are presented for the basic telescope fabrication, for the modifications, and for the construction of a complete facility.

2. RELEIGHTON TELESCOPE

Five telescopes are currently in use in an array configuration for millimeter and submillimeter astronomical measurements at the Owens Valley Radio Observatory (OVRO, near Bishop, CA) and one is in use at Mauna Kea, HI. The first operational telescope was deployed at OVRO in 1978 and is still in use. The OVRO telescopes observe both during the day as well as at night and do not have enclosures, while the Hawaii telescope, Figure 1, uses a hemispherical dome to protect it from the environment, and observes 010% at night.

The primary mirror is a 10.4 m diameter clear aperture paraboloid consisting of 84 panels of sandwich construction. Each panel consists of a facesheet and backsheet of aluminum epoxied to a double honeycomb core of hexagonal aluminum cells. The axis of symmetry through the hex core cell center is perpendicular to the sheets. There are fourteen sizes of panels comprising the primary, the panels on the outer diameter are four, five, or six sided irregular shapes, the remaining interior panels are approximately hexagons. The primary is attached at ninety-nine points to a tubular steel space truss structure, in turn attached to the tracking gimbal at nine points which lie in a plane parallel to the aperture.

The fabrication of the primary follows a unique process, essentially unchanged since the concepts were defined in 1971⁷. The backup truss structure is first assembled and mounted directly to a large air bearing. Each panel is coarsely cut from a planar sheet of material to the necessary shape and attached to the truss. At this stage the panels consist of the backsheets and cores only, no facesheets. After all 84 panels are cut, positioned, and attached to the truss, the paraboloid figure is cut directly into the hex core by rotating the entire structure into a cutting tool fixed to a 5.2 m long parabolic track fixture. The tools are carbide tipped table saw blades and knife edged high speed tool steel slicing blades. Many small cuts are made so that very little heat is dissipated by the low density material. It takes about 3 weeks to bring the paraboloid to within about 3 mm of its final side face. Temporary tensioning bars are then attached to the panel backs to exert pressure to push the center of a panel up a predetermined amount and pull the corners downward equally, causing the center of a panel to be cut deeper than the corners. The facesheet elastic deformation (as much as $10 \mu\text{m}$) will restore each panel to the proper shape when the facesheet is later epoxied to the machined core. For the final cuts of the core, the air temperature must be quite stable ($\pm 1 \text{ K}$) and the cuts take 12-24 hours for a complete pass. When the figure is deemed acceptable, the panels are removed and the 1.3 mm thick facesheets are epoxied to the panel core under vacuum bagging. Lastly, the corners of three panels are bolted together to a plate, in turn attached to a manually adjustable standoff which bolts to the truss. The standoff takes the strain due to the

thermal expansion difference between the steel truss and aluminum panels. The paraboloid's surface figure is verified by measuring its deviation from a template, which is attached to the machining fixture, by transducer measurements, and holographic measurements using astronomical Sources.

For the telescope in Figure 1, the total fabrication surface error, including errors in the fixture, alignment of the fixture and surface, control of temperature, panel warp, cutting, facesheet finish, and reassembly is $9\text{--}13\text{ }\mu\text{m}$ ($1\text{ }\sigma\text{ rms}$)⁸. The accuracy of the surface measured on a scale larger than 40 mm is about $5\text{ }\mu\text{m}$, and for scales less than 10 mm it is determined by the $2\text{ }\mu\text{m}$ finish of the mill-supplied facesheet.

Note that the backup support structure used to hold the primary during machining will be the one actually used in the field. This feature, along with the use of precision struts and pinned joints allows the primary and backup structure to be disassembled for shipment and accurately reassembled at the site obviating the need for extensive readjustment. The cost of fabricating the primary by this process is independent of the number of panels and their shapes - the machining fixture is designed to cut only this paraboloid, and the panels and backup structure are all fastened together to form a rigid integral body with a nearly continuous surface area.

The primary will deform under gravity loading as the telescope is pointed, but as the telescope is homologous by design and through construction, the coarse resultant change is a shift of the focal point from its nominal best location (focal shifts are less than 1 mm over 90 degrees of elevation angle). The secondary shifts its position as well, but generally tracks the shift in paraboloid focus. Additionally, it can be adjusted along the axis of the telescope and independently in a plane perpendicular to the axis by 25 mm. Lastly, the primary may be tuned to give the best overall parabolic figure (in an rms sense) at any position by manually adjusting the standoffs that attach the panels to the backup truss. Nighttime measurements of gravitationally induced distortion across the entire primary were $10\text{--}40\text{ }\mu\text{m rms}$ after removing focus, tip/tilt, and secondary centering, for zenith angles between 15 and 65 degrees. At least at night, the systematic errors of the telescope are controllable, to the degree required for the communication photon bucket receiver, and performance is then limited by the random figure error achievable in the panels.

3. OPTICAL MODIFICATIONS

Performance estimates for a Leighton telescope used as an optical communications receiver have been made. A model of the Leighton telescope having the prescription displayed in Table 1 was input into the Controlled Optics Modeling Package (COMP) code⁹. Errors modeled included surface figure, tip/tilt, and piston. The primary was modeled as a segmented aperture of 84 panels and surface figure errors were assigned to it. The blur diameter at the Cassegrain focus was used as the optical figure of merit to gauge expected performance of this photon bucket and was compared to previously derived requirements for DSORA.¹⁰ Figure 2 displays the blur size, at the focus for a primary having a $1.0\text{ }\mu\text{m}$ ($1\text{ }\sigma\text{ rms}$) figure error over a correlation distance of 1 in, with residual errors of $25\text{ }\mu\text{rad}$ of tip/tilt and $60\text{ }\mu\text{m}$ of piston error per panel. All rays are shown, and more than 95% of them are contained within an $86\text{ }\mu\text{rad}$ full angle blur circle. The desired DSORA performance is $100\text{ }\mu\text{rad}$.

A requirement for scatter from the telescope optics was derived. It is desired to suppress the scattered light due to solar illumination of the optics to levels below that of expected communication return signals from earth-planet links. Link calculations to Plute, a stressing Gist, indicated that received signals as low as 1 pW at the ground at a wavelength of 532 nm are possible. A margin of 100 was applied to account for uncertainties in link parameters, and this resulted in a requirement for the BRDF (Bidirectional Reflectance Distribution Function) for both the primary and secondary mirrors of $1.4 \times 10^{-3}\text{ sr}^{-1}$ at 10 degrees off normal at 500 nm.

Bare aluminum cannot be polished to a degree necessary to obtain a BRDF of this magnitude. A plating of electroless nickel (ENi) of about $100\text{--}150\text{ }\mu\text{m}$ thickness can be applied to aluminum. The part must be near net-shape before plating. The nickel surface may then be figured and finely polished to achieve this BRDF.

In operation, the receiver must accommodate a range of possible spacecraft transmitter wavelengths: $500\text{--}2000\text{ nm}$. The best choice of optical coating for this range is a metal, either silver or aluminum. It was decided to select an enhanced aluminum coating. Aluminum coating longevity is at least 3-5 years and the dielectric overcoatings applied for enhancement at selected wavelengths protect the aluminum layer from oxidation and evaporation. It is likely that an

enhancement of the reflectance will be sought at the laser wavelengths of 1060, 532, and in the band 750-860 nm.

A layup of the proposed primary mirror is shown in Figure 3. The basic fabrication process for the primary as described above is retained, which includes the backsheet, core structure, and facesheet - a layer of INi is plated onto the facesheet. This layer is then figured, and polished to achieve the BRDF specified above, then an enhanced aluminum coating is applied.

Additional specifications for the primary and secondary mirrors are shown in Table 2. The figure quality for the primary specified is $5\text{ }\mu\text{m}$ over 1m correlation distance uniformly, providing some margin for inevitable material instability over time, estimated to be 1 -2pm per year for aluminum¹¹. For this figure quality, and with 25 μrad tip/tilt and 60 μm piston per pane.] as above, the expected blur size, at focus is about 50 μrad (> 95% of all rays). The secondary figure quality is 1-1.5 μm rms over the full aperture, a readily achievable value. The telescope performance is ultimately limited by the primary mirror figure quality as fabricated.

4. GROUND TERMINAL FACILITY COST

The Table Mountain Facility (TMF) located near Wrightwood, California at an altitude of 2.3 km was nominally selected as the site for locating the ground terminal. It is desirable to reduce new construction cost by utilizing existing infrastructure whenever possible - several optical telescopes already are in place at this JPL owned and operated facility. The cost was estimated to construct a modified Leighton receiver, enclosure, and new service building at TMF and use basic existing utilities, service roads, and support buildings such as meeting rooms and storage area.

An enclosure design was found for the telescope which was estimated to cost approximately half that of the dome shown in Figure 1. This enclosure consists of four rings, is approximately 22 m in diameter and 16 m high when fully open, and collapses downward to a single ring to deploy the telescope for operation. A new service building of some 186 square meters (2000 square feet) is required. The concept for the entire facility is shown (not to scale) in Figure 4. The enclosure protects the telescope from snow and severe wind up to 200 km/hr, but the telescope is otherwise, exposed to ambient conditions during operation. The site would occupy less than 1 acre.

The cost estimated to construct the entire facility is given in Table 3. Note the low cost for the basic Leighton telescope fabrication, \$1.8 M, including a gimbal capable of tracking from sidereal rates to about 30/s, sufficiently fast to track low earth orbiting satellites. Modifications to the telescope optics, which include a completely new secondary, are about \$3.3 M. Beam train optics follow the secondary and relay the beam to detectors. These are primarily a beam reducing telescope, two axis beam steering mirror, beamsplitters, and other small focusing optics which will deliver the beam to both acquisition and communication detectors. Detectors and other electronics are not included in these estimates. A Coudé beam path was designed and included.

A nominal schedule is shown in Figure 5. The total time to build the telescope, modify the optics, fabricate the enclosure and gimbal, prepare the site, erect the building and then install the hardware is three years. About nine months and three people are needed to construct the primary, secondary, and backup structure. The time required to plate, figure, and polish the primary is about two years, during which the secondary can also be fabricated. The schedule indicates two parallel efforts to reduce this time to one year. Three months are needed to coat both optics. The gimbal and enclosure can be fabricated in two years. Signal processing electronics and software development are not included in the cost estimate; this activity is shown on the schedule as a two year effort. The starting activity upon receipt of funding is a facility engineering report, and initial operating capability is projected at five and one-half years later.

5. CONCLUSION

It was shown that a ten meter class photon bucket can be created by optically modifying an existing radio telescope design and construction process. The overall cost to produce the bucket by this method is much lower than a comparably sized telescope fabricated using conventional optical telescope techniques. New facility expenditures are further lowered by utilizing existing sites and cost sharing whenever possible.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. K. Shaik, "Progress on Ten Meter Optical Receiver Telescope," *Proc. SPIE*, Vol. 163S, pp.109-117, 1992.
2. B. Kerr, "Architectural Design of a Ground-Based Deep Space Optical Reception Antenna," *Opt. Eng.*, pp. 446-451, April, 1991.
3. B. Kerr and K. Shaik, "A Ten Meter Optical Telescope for Optical Communications," *Proc. SPIE*, Vol. 1236, pp. 347-350, 1990.
4. K. Shaik, D. Wonica, and M. Wilhelm, "Optical Networks for Earth-Space Communications and their Performance," See *current SPIE Conf. Proc.*, 1994.
5. R. Gagliardi and S. Karp, *Optical Communications*, Chap. 8, John Wiley & Sons, NY, 1976.
6. B. Yin, *Anomalous Dispersion Optical Filters*, Ph.D. Dissertation, New Mexico State University, Las Cruces, NM, 1993.
7. R.B. Leighton, *A 10-Meter Telescope for Millimeter and Submillimeter Astronomy*, Final Technical Report for NSF Grant AST 73-04908, May, 1978.
8. D. Woody, D. Vail, and W. Schaal, "Design, Construction, and Performance of the Leighton 10.4 Meter Diameter Radio Telescopes," to be published in *Proc. IEEE*, May 1994 (special issue on Radio Telescopes).
9. D. Redding, C. I Draper Laboratory, Cambridge, MA, J. Needels, K. Wallace, and M. Levine, Jet Propulsion Laboratory, Pasadena, CA, *Controlled Optics Modeling Package (COMP) User Manual*, Release 1.0, May 15, 1992.
10. See reference 1.
11. D. Vukobratovich, "Aluminum and Aluminum/Silicon Carbide Metal Matrix Composites for Optical Systems," in *Proc. of Aluminum, Beryllium, and Silicon Carbide Technologies Seminar*, Oak Ridge National Laboratory, Oak Ridge TN, Feb 23-24, 1993.

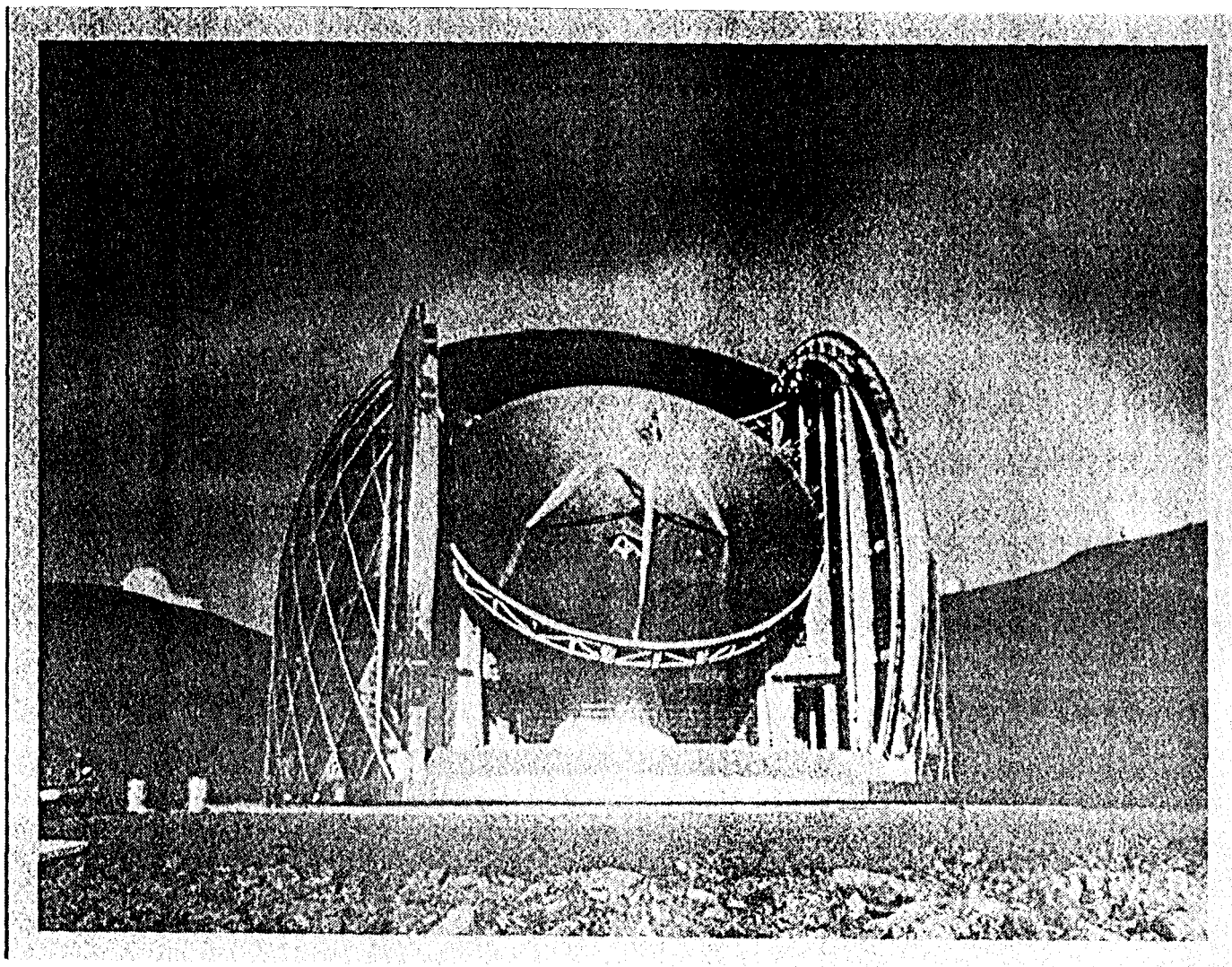


Figure 1. Leighton RF telescope at Caltech Submillimeter Observatory, Mauna Kea, HI showing the unpolished aluminum primary. The primary clear aperture is 10.4 m. The dome rotates with the telescope and is about 18 m in diameter at the base, 13 m high. (Photo courtesy of D. Vail, California Institute of Technology).

TABLE 1. OPTICAL TELESCOPE PRESCRIPTION

System Focal Length	92.77
System Focal Ratio	8.920
Primary Mirror Diameter, m	10.4
Primary Mirror Focal Ratio	0.40
Primary Conic Constant	-1
Primary to Secondary Distance, m	3.887
Secondary Mirror Diameter, m	0.60
Secondary Mirror Focal Ratio	0.39
Secondary Conic Constant	-1.1909
Primary to Cassegrain Focus, m	1 5 2 4

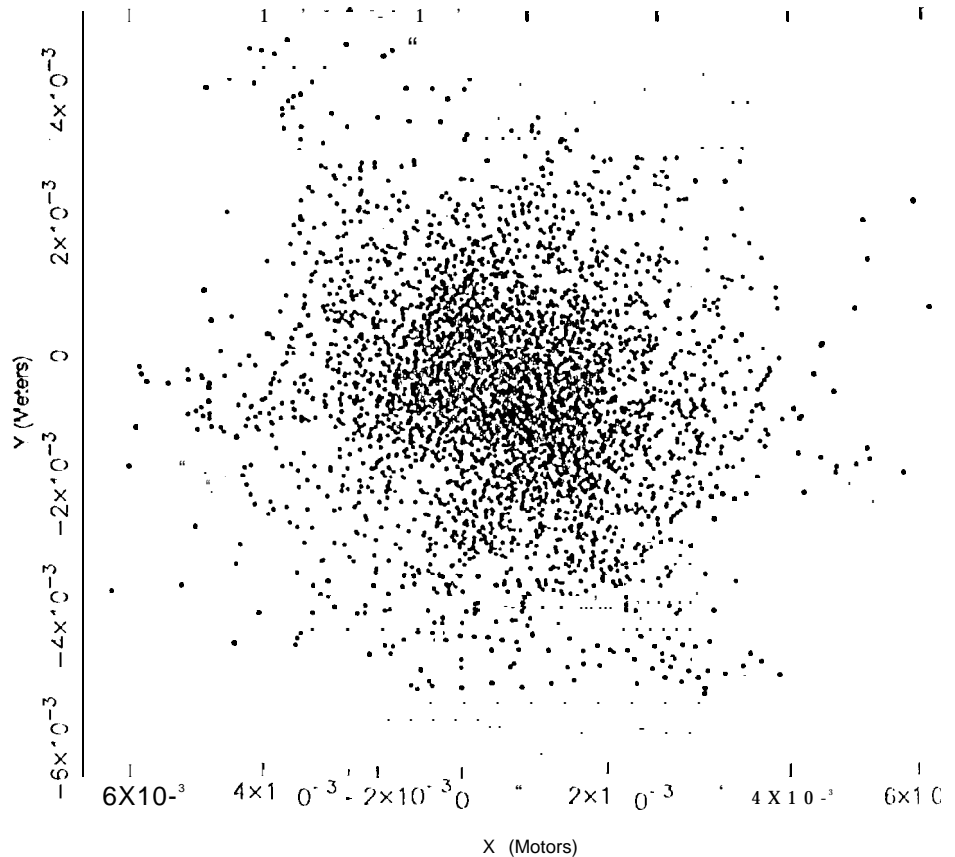


Figure 2.

Spot diagram at Cassegrain focus from COMP (Controlled Optics Modeling Package) analysis. The scale is in meters. Approximately 4700 rays were launched. The primary was modeled as an 84 segment aperture each segment of hexagonal shape. The figure quality was $10 \mu\text{m}$ ($1 \sigma \text{ rms}$) over 1 m correlation distance, with $2.5 \mu\text{m}$ ($1 \sigma \text{ rms}$) of tip/tilt, and $60 \mu\text{m}$ ($1 \sigma \text{ rms}$) of piston applied to each panel. The total blur size is about $86 \mu\text{rad}$.

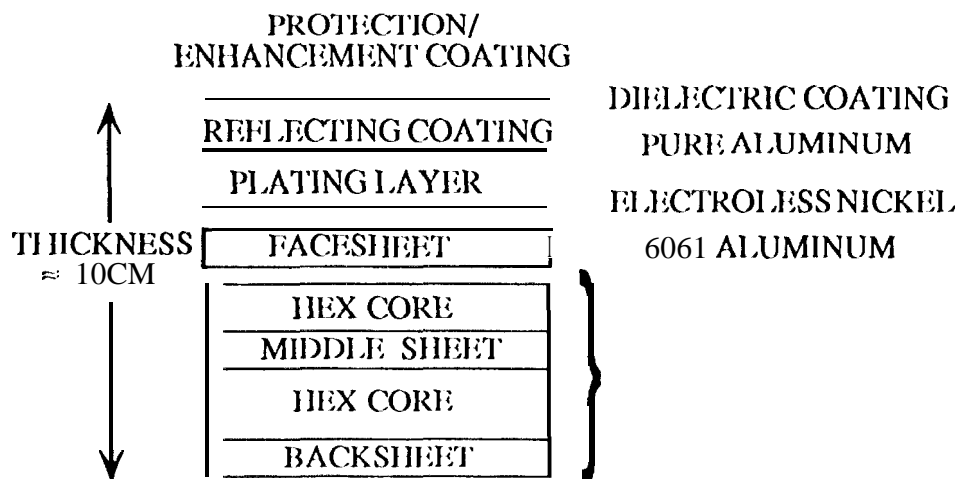


FIGURE 13. Layup of Primary Mirror for Photon Bucket

TABLE 112. MIRROR SPECIFICATIONS

PRIMARY MIRROR	
Geometry	Concave Paraboloid, 84 Segments 10.4 m Diameter, F/0.4
Substrate	6061 Aluminum 1 Facesheet 3003 Aluminum Core & Backsheet
Plating	Electroless Nickel
Figure	5 μm over 1 M Correlation Distance
Scatter	$1.4 \times 10^{-3} \text{ sr}^{-1}$ @ 10° @ $\lambda = 0.5 \mu\text{m}$
Reflectance	Avg. $\approx 93\%$ over $\lambda = 0.5\text{-}2.0 \mu\text{m}$ Enhanced at Selected Wavelengths
SECONDARY MIRROR	
Geometry	Convex Hyperboloid, One Piece, 60 cm Diameter, F/# $\geq F/0.40$
Substrate	6061 Aluminum
Plating	Electroless Nickel, (Same as Primary)
Figure	1-1.5 μm (rms) over 60 cm
Scatter	$1.4 \times 10^{-3} \text{ sr}^{-1}$ @ 10° @ $\lambda = 0.5 \mu\text{m}$
Reflectance	Avg. $\approx 93\%$ over $\lambda = 0.5\text{-}2.0 \mu\text{m}$ Enhanced at Selected Wavelengths

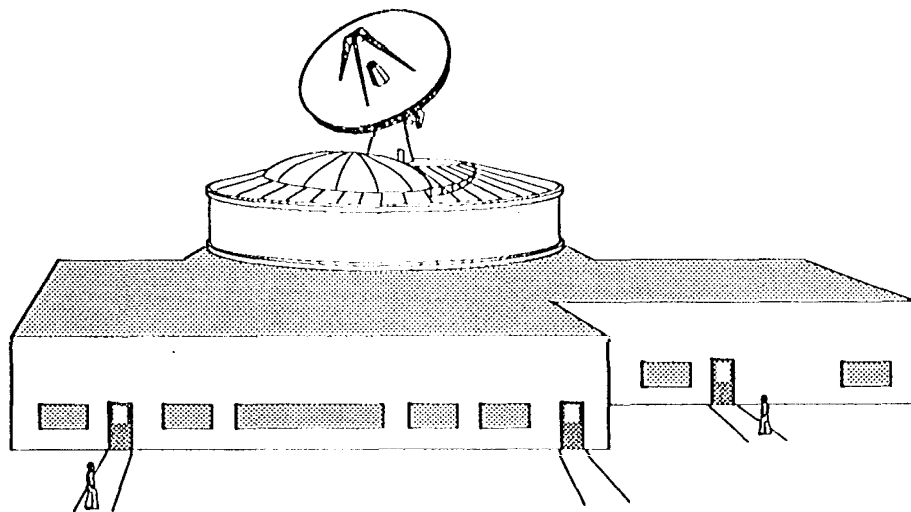
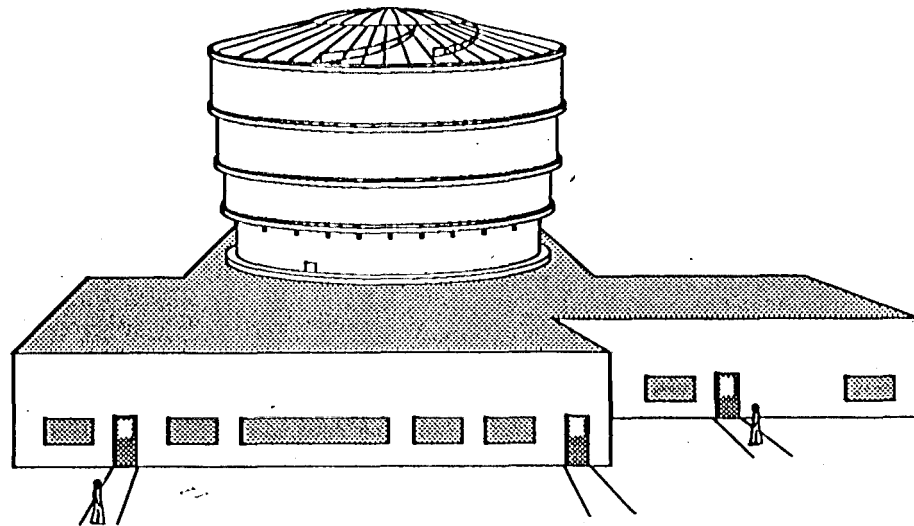


Figure 4. Concept for Facility. The telescope and its enclosure are both on top of the service building. In the upper figure, the enclosure is closed, in the lower figure it is opened, exposing the receiver.

TABLE 113. FACILITY COST SUMMARY (1993 DOLLARS)

Facility Item	\$K	\$K
Telescope		
Primary & Backup Support Structure	1065	
Gimbal (includes controller)	433	
Motors, Bearings, Encoders	155	
Baffles, Structural Modifications	170	
Subtotal Telescope		1823
Optics Modifications		
Primary (plate, figure, polish, coat)	2268	
Proof Panels	225	
Tooling	500	
Metrology	250	
Secondary (new)	63	
Subtotal Optics Modifications		3306
Beam train optics		400
Coudé Beam Train Optics		165
Site Development & Utilities		250
Foundation, Enclosure, Service Building		3343
Transportation & Shipping		50
Installation & Integration at Site		743
Total		10080

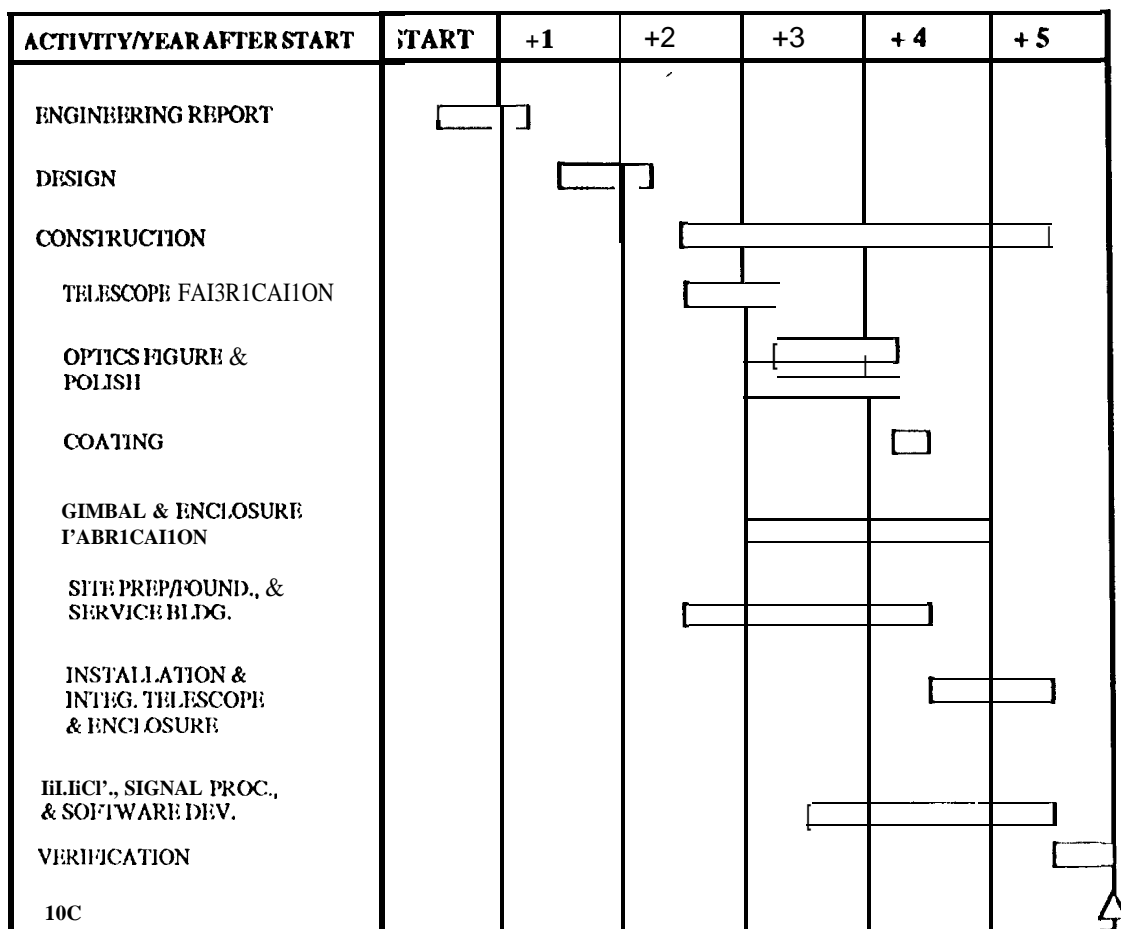


FIGURE 5. Schedule for Construction of Photon Bucket and Facility.